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Photo detachment of negatively charged Muonium in GaAs by laser irradiation

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Abstract

Photo detachment of negatively charged muonium was successfully observed the first time, with wide range wave length from 800nm to 1450nm lasers in n-type GaAs at 15 K. Recently, Lichti *et al.* determined the energy levels in the band gap of T center muonium (as an acceptor) and BC muonium (as a donor) by reanalysis of the existing data obtained by various μ SR techniques for several semiconductors like Si, Ge, GaAs, GaP etc. In these semiconductors, GaAs is one of the best sample to apply the negatively charged muonium photo detachment method, because the energy level of T center muonium is above 0.54 eV from the valence band, therefore the ionization energy for $\text{Mu}_T^- \rightarrow \text{Mu}_T^0 + e^-$ is 0.98eV (corresponding laser wave length is 1260nm), which is within the region of present OPO laser system produced, which was installed RIKEN-RAL

Keywords: Laser μ SR; Photo detachment; Muonium minus;

1. Introduction

Hydrogen is a ubiquitous impurity in most semiconductors, including elemental (e.g., Si), compound (e.g., GaAs) one. Theoretical modeling of hydrogen impurities in semiconductors carried out over a period of many years has produced the accepted picture of H behavior in these materials [1], albeit with rather meager direct experimental evidence for the isolated atomic defect except in Si. The indirect verification of these models is mostly from results on the muonium spectroscopy. Isolated hydrogen is typically a negative-*U* center, where $U = E_A(-/0) - E_D(0/+)$ is the separation between donor and acceptor thermodynamic levels. Consequently, in most semiconductors, hydrogen shows compensating properties, existing as H^+ in *p*-type and H^- in *n*-type materials under equilibrium conditions.

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Isolated hydrogen can exist in three charge states, H^+ , H^0 , and H^- , with the ionic centers residing at different interstitial sites. For predominantly covalent cubic materials, H^+ is stable at or near the center of a stretched bond [bondcentered (BC) site] and H^- is stable in the large tetrahedral void (T site) of the diamond or zinc-blende structure. Both of these sites can support a neutral center, but the electronic wave functions and the hyperfine interactions are vastly different at the two locations. When H^0 resides in the void, it is simply an interstitial impurity atom with a large isotropic hyperfine constant, somewhat reduced from the free-atom value by relatively small overlaps with near neighbors. However, in forming H_{BC}^0 , hydrogen has reacted with the host to form a radical in which the unpaired electron resides in antibonding orbitals on its two nearest neighbors, producing a small anisotropic hyperfine interaction.

Recently, Lichti *et al.* determined the energy levels in the band gap of T center muonium (as an acceptor) and BC muonium (as a donor) by reanalysis of the existing data obtained by various μ SR techniques for several semiconductors like Si, Ge, GaAs, GaP etc [2,3]. To check these values by independently and directly, the laser photo ionization of muonium in these semiconductors is one of the best methods. And if this method works well, it is also applicable to the muonic oxygen atom, which is nitrogen atom analog in oxide semiconductors like ZnO or TiO_2 , where nitrogen impurities are recently considered to play key roles in the developments.

Among several semiconductors, GaAs is one of the best sample to apply the muonium photo detachment method for the first time, because the energy level of T center muonium was observed above 0.54 eV from the valence band, therefore the ionization energy for $Mu_T^- \rightarrow Mu_T^0 + e^-$ is 0.98 eV (corresponding laser wave length is 1260 nm), which is within the region of existing OPO laser system produced.

2. Experiment

The experiment was conducted at Port 2 of the RIKEN-RAL Muon facility at ISIS of Rutherford Appleton Laboratory (UK) by using pulsed (a double pulse with 75 ns width and 350 ns separation with 50 Hz repetition) 4 MeV positive muon beam. The sample used was 360 μ m of thickness 50.8 mm diameter single crystalline GaAs with $3 \times 10^{16} \text{ cm}^{-3}$ Si doping. The [001] axis was placed along muon/laser direction.

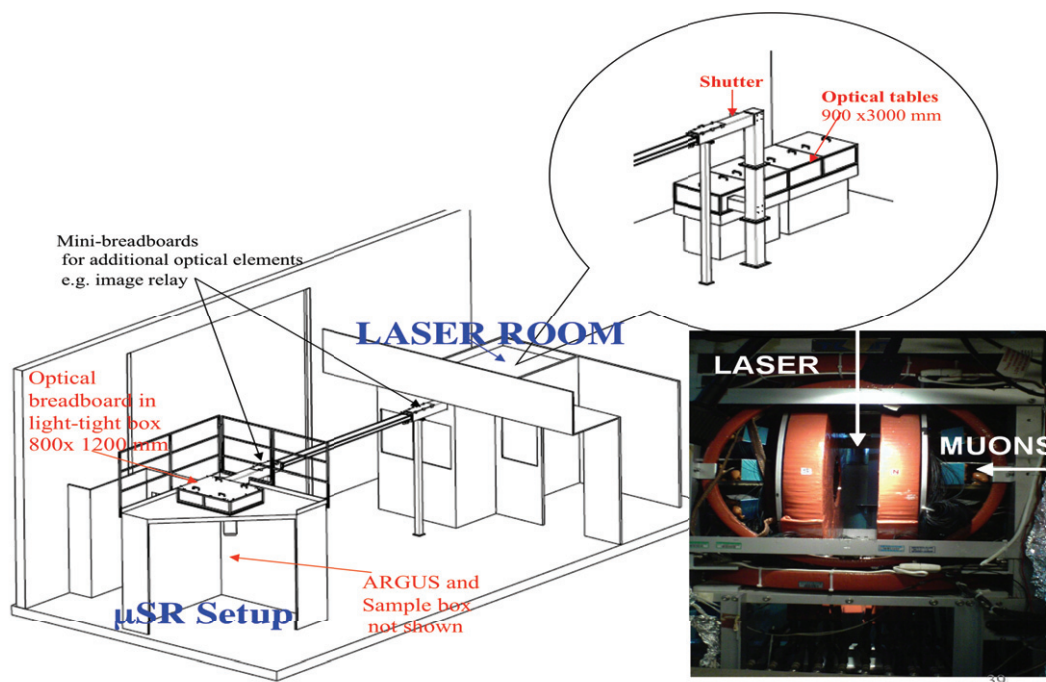


Fig.1 Laser μ SR setup at RIKEN-RAL Muon Facility.

The tunable laser light with repetition frequency of 25 Hz was generated using a widely tunable OPO (Opt Parametric Oscillation) system (Continuum Panther EX OPO) pumped by 355 nm beam from Continuum Powerlite 9025 Nd:YAG laser. The linearly polarized laser output was transported through a light-tight enclosure to optical breadboard located in the muon beam port above the muon spectrometer at a distance of ~8 m using 9 silver mirrors. The laser pulse energy over the sample could be varied using a computer controlled attenuator up to 3 mJ/pulse.

At the ending part of the laser transport, a sample box with He-flow cryostat was installed. The second laser steering prism was placed right at the downstream of the muon beam so that the laser light is injected to the rear side of the sample through fused-quartz window. Sample was placed in a strain-free manner in a specially designed sample holder containing He gas. Care was taken for the muon beam not to be stopped at neither mirror nor cold plate. All measurements are performed under zero field condition, where only diamagnetic component (here Mu_T^-) is observed. At zero field, Mu_T^0 is expected to lose their polarization immediately, due to large nuclear hyperfine interaction with surrounding Ga and As.

Preliminary data is shown in Fig.2. Around 1.4 to 1.5 eV, a large asymmetry drop were observed, these are the effect of the interactions between Mu_T^- and photo excited electron, which is already established in the previous study [4,5]. Around 0.9 to 1.2 eV, a clear bump was shown, which cannot be explained by the above picture. The most reasonable explanation is the effect of direct photo ionization of Mu_T^- and Mu_T^0 lose their polarization. The photo detachment cross section of negatively charged Hydrogen was measured to be $4 \times 10^{-17} (\text{cm}^2)$ [6]. And the typical photon flux in our measurement was about $6 \times 10^{15} / (\text{cm}^2)$, therefore, if we assume the cross section is the same order in GaAs, a few ten percent ionization probability is expected. The data clearly shows the effect was observed below 0.98 eV. The detailed analysis with the theoretical model to determine the energy levels in the band gap is now under progress.

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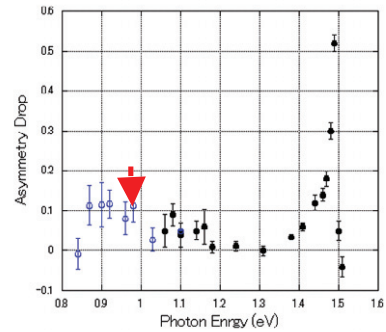


Fig.2 The photon energy dependence of the asymmetry change of Mu_T^- in GaAs under laser irradiation. The data plotted with closed (open) circle were obtained at 2009 (2010). Asymmetry change is normalized by laser power. The arrow shows the ionization energy of Mu_T^- , determined by Lichti *et al.*